EO-1 Advanced Land Imager Pre-Flight Calibration[1]

J. A. Mendenhall, D. E. Lencioni, D. R. Hearn, A. C. Parker

Massachusetts Institute of Technology – Lincoln Laboratory, 244 Wood Street Lexington, MA 02173

ABSTRACT

The EO-1 Advanced Land Imager (ALI) is the first earth-orbiting instrument to be flown under NASA's New Millennium program. The ALI employs novel wide-angle optics and a multispectral and panchromatic spectrometer. EO-1 is a technology verification project designed to demonstrate comparable or improved Landsat spatial and spectral resolution at a substantial cost saving. This paper provides an overview of ground calibration and performance assessment of the Advanced Land Imager. Included are techniques for calibrating and assessing spatial (focus, MTF, pixel line-of-sight), spectral (resolution, cross-talk, out-of-band response), and radiometric (linearity, offset) parameters for this instrument. Additionally, the pre-flight technique used to verify in-flight solar calibration is discussed.

Keywords: remote sensing, Landsat, spatial calibration, spectral calibration, radiometric calibration

1. INTRODUCTION

The Earth Orbiter I Advanced Land Imager is a technology verification instrument under the New Millennium program (Figure 1, Lencioni and Hearn (1998), Digenis et al. (1998)). The ALI contains wide angle optics designed to provide a continuous 15° x 1.625° field of view without the use of a scan mirror. The focal plane for this instrument is partially populated with four sensor chip assemblies (SCA) and covers 3° by 1.625°. Each SCA contains 9 multispectral bands (30 meter resolution) and a single panchromatic band (10 meter resolution, Table 1). These bands have been designed to mimic six Landsat (Lauer et al., 1997) bands with three additional bands covering 0.433-0.453, 0.845-0.890, and 1.20-1.30 μm. The ALI is currently scheduled for launch in late May 1999 and will fly one minute behind Landsat-7. In this configuration, both instruments will view identical scenes in order to verify the spatial, spectral, and radiometric performance of the ALI.

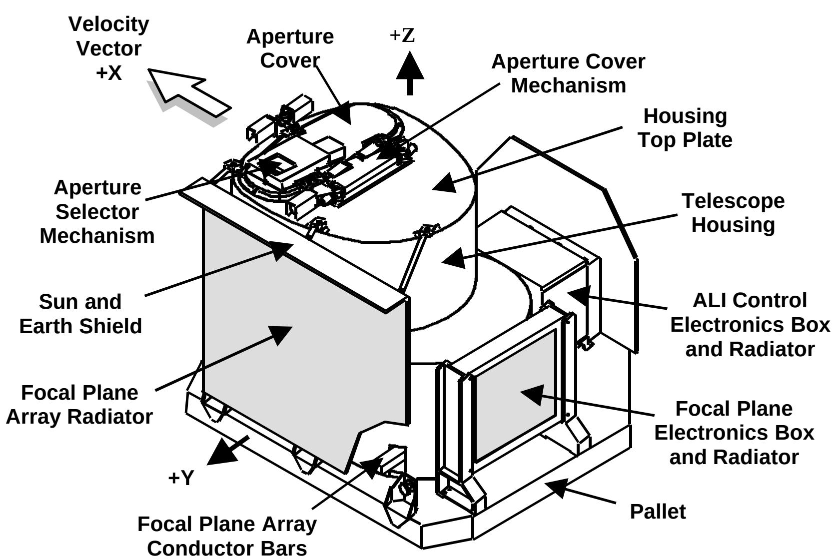

Figure 1: Earth Orbiter 1 Advanced Land Imager.

[1] This work was sponsored by NASA/Goddard Space Flight Center under U.S. Air Force Contract F19628-95-C-0002

Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Air Force.

Band	Wavelength (μm)	Ground Sampling Distance (m)
Pan	0.48 – 0.69	10
MS-1’	0.433 – 0.453	30
MS-1	0.45 – 0.515	30
MS-2	0.525 – 0.605	30
MS-3	0.633 – 0.69	30
MS-4	0.775 – 0.805	30
MS-4’	0.845 – 0.89	30
MS-5’	1.2 – 1.3	30
MS-5	1.55 – 1.75	30
MS-7	2.08 – 2.35	30

Table 1: Spectral and spatial definitions for the ten EO-1 ALI bands.

Ground calibration of the Advanced Land Imager is scheduled to begin in September 1998 at the Massachusetts Institute of Technology Lincoln Laboratory. For three months, the ALI will be subjected to a series of tests designed to examine and calibrate the spatial, spectral, and radiometric properties of this instrument. This paper provides a description of the calibration procedures that will be used during that period.

2. CALIBRATION LABORATORY

The calibration of the EO-1 ALI will be performed in a class 1000 clean room at Lincoln Laboratory. Initial checkout, focal plane alignment, and verification of the in-flight solar calibration technique will be conducted on a clean bench or Flowtron fixture and operated under ambient conditions. For all other phases of calibration the ALI will be placed in a

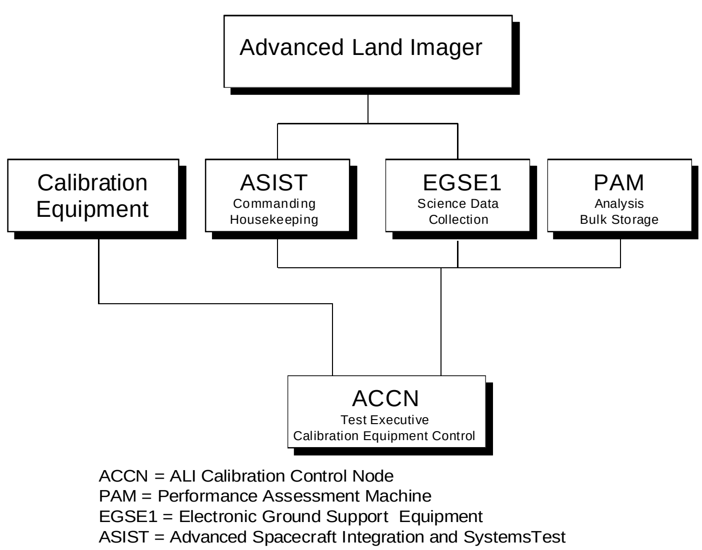

Figure 2: Configuration of ground support equipment during pre-flight testing and calibration of the EO-1 ALI.

vacuum chamber and operated at a pressure < 1 x 10^{-7} torr. The focal plane will be cooled to flight temperature (220 K) via radiative coupling of instrument radiators to a liquid nitrogen refrigerated shroud lining the inner surface of the vacuum tank.

Control of calibration sequences and equipment will be provided by the ALI Calibration Control Node (ACCN) LabVIEW based personal computer (Figure 2). Commanding and housekeeping monitoring of the ALI will be conducted by the RS2000 Advanced Spacecraft Integration and Systems Test (ASIST) computer. Data acquisition will be provided by the Unix based Electrical Ground Support Equipment (EGSE1) computer and a Silicon Graphics Performance Assessment Machine (PAM) will store and process focal plane data in real time.

3. SPATIAL CALIBRATION

The spatial testing and calibration of the EO-1 ALI include focal plane alignment with the flight telescope, determination of the modulation transfer function at various positions along the focal plane, and determination of the pixel lines-of sight.

Imaging Collimator

The imaging collimator used for all phases of spatial calibration is depicted in Figure 3. The collimator resides on a 3'x9' optical table and has a 3.2° diameter field of view with an unobstructed aperture. An Oriel 250 W quartz tungsten-halogen lamp is used as a source of stable broadband emission from 350-2600 nm. A six-inch diameter integrating sphere is attached to the output of the lamp housing and is used to provide a flat, diffuse source across a 1.5 inch port. A condensing lens is placed in front of the integrating sphere exit port to expand the diffuse source, provide the 3.2° field of view for the collimator, and fill the entrance pupil of the ALI. The 30/30 beamsplitter is used to move the source beam to a convenient location on the optical table and a 30 cm diameter, 1.5 m focal length spherical mirror is used to collimate the incident beam. A field-flattening lens is placed near the focus of the spherical mirror to flatten the focal plane over the field of view. Once the beam has been collimated, it is directed back through the beamsplitter, passing through a vacuum tank window and into the entrance aperture of the ALI. Finally, a chrome-on-glass 1951 USAF target or other reticles are placed at the focus of the imaging collimator to produce a series of knife-edges focused at infinity. This reticle is mounted on a motorized stage that may be translated in X, Y, or Z as needed throughout spatial calibration.

Determination of Modulation Transfer Function

The modulation transfer function of the EO-1 ALI will be measured at several positions using a scanning knife-edge. A reticle with precisely defined vertical or horizontal knife edges will be positioned at the focus of the imaging collimator. The reticle is translated horizontally or vertically using motorized stages to produce a series of precisely controlled scanning knife-edges. For each scan, a single knife-edge translates five to ten pixels at a velocity of 100 μm/s while the ALI records focal plane data at a frame rate of 226 Hz. As a result, a single 40 μm x 40 μm multispectral pixel will be sampled twenty times as the focused knife-edge is scanned across its surface. Plotting a pixel's intensity as a function of time represents an edge-spread function (for that pixel) for a particular scan. A line spread function for that pixel is produced by differentiating the edge-spread function. Finally, the modulation transfer function is generated by the taking the Fourier transform of the line-spread function. In order to repress noise associated with a particular scan, ten neighboring pixel's MTF's will be averaged to represent the transfer function for a particular region of the instrument's field of view. This process is then repeated using vertical scans and at several locations to map the modulation transfer function across the focal plane.

Determination of Best Focus

Focal plane alignment or determination of best focus (tip, tilt, and Z displacement) is accomplished through an iterative process of MTF measurements as described in the proceeding paragraph, and shimming. First, a knife edge is placed at the focus of the imaging collimator and the modulation transfer function of the instrument at various positions along the focal plane is measured using horizontal and vertical scanning knife edges. The position of the reticle relative to the focus position of the imaging collimator spherical mirror is then moved a distance of 0.1 mm and the measurement of the modulation transfer function across the focal plane is repeated. This process is repeated for several reticle Z positions. For each Z position, the MTF for each pixel is integrated to a predefined frequency. This integration forms a figure-of-merit for the determination of best focus. Best focus for pixel *j* corresponds with the Z position that results in the highest figure-of-merit for that pixel. In this manner, best focus for several pixels across the focal plane may be determined.

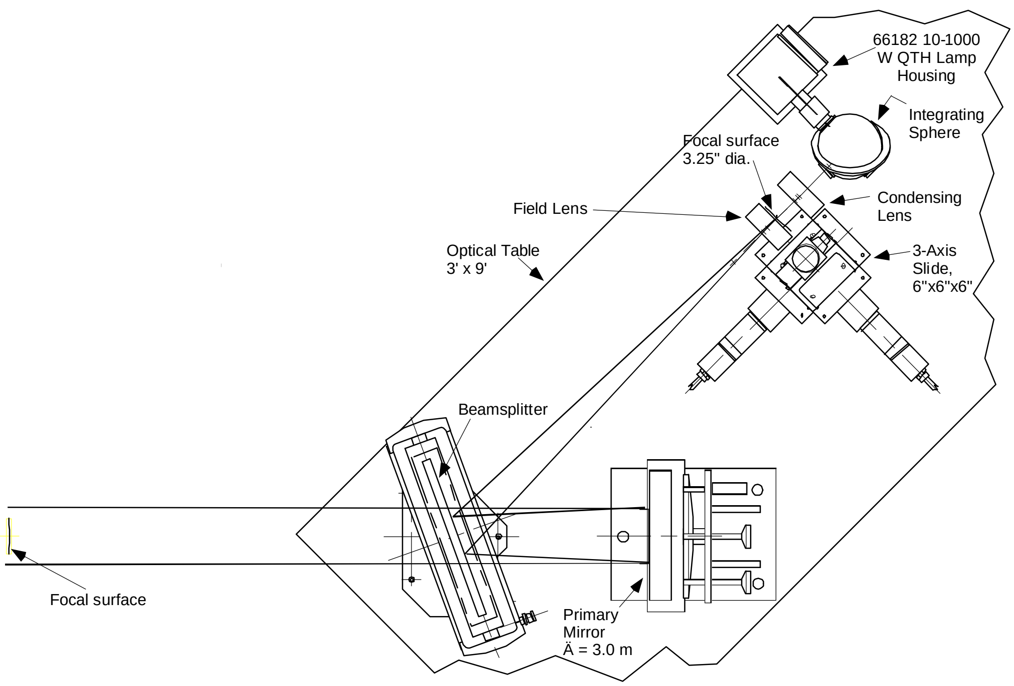

Figure 3: Spatial collimator used during focus, MTF, and pixel line of sight determination.

From these measurements, the focus error of the ALI at each pixel may be calculated as

$$Z_{err}=(f_{ALI}/f_{coll})^2\Delta Z_{opt}$$

Here, f_{ALI} is the focal length of the ALI, f_{coll} is the focal length of the collimator, and ΔZ_{opt} is the best focus position for that pixel, relative to the infinity focus. The focal plane is then shimmed according to the calculated focus errors across the focal plane. This process continues for as many iterations as necessary until best focus is obtained for the instrument.

Determination of Pixel Lines of Sight

Another important parameter to be measured during spatial calibration of the EO-1 ALI is the focal plane pixel lines of sight. The pixel lines of sight map specifies the geometric look direction of each pixel and must be well understood to properly reconstruct a ground scene. Factors that must be considered when constructing a line of sight map include alignment of pixels relative to one another, alignment of sensor chip assemblies relative to one another, and geometric distortion produced by the telescope.

The pixel lines of sight mapping process centers on the generation of a predicted reticle image replicating an original reticle geometry. Initially, a Ronchi ruling with a precisely defined vertical pattern is projected as a static image into the entrance aperture of the EO-1 telescope using the imaging collimator, and the focal plane response is recorded. Similar images are recorded for the reticle rotated by 60° and 120° and for reticles with different ruling frequencies. A synthetic reticle image is then constructed using the known reticle pattern, the reticle orientation, the sensor chip assembly layout, and the initial estimates of other parameters to be fitted. These parameters include the ALI focal length, measured sensor chip assemblies positions on the focal plane, measured pixel positions within a sensor chip assembly, and telescope distortion coefficients. Initial values of these parameters are obtained from subsystem measurements. A difference image is then generated by subtracting the synthetic image based on the original reticle geometry from the measured image. Fitted parameters are adjusted and a second synthetic image is generated. This process continues by a least-squares fitting process until a final set of parameters is derived which minimizes the mean-squared value of the difference image. These parameters are then used to generate the pixel lines of sight map, which will be used to correct subsequent imaging performed by the ALI.

4. SPECTRAL CALIBRATION

The purpose of the EO-1 ALI spectral calibration is to measure the spectral response of the mutispectral and panchromatic detectors in flight configuration under flight conditions. The filters that define these bands have previously been measured under ambient conditions at the wafer level and the PIN and HgCdTe detector quantum efficiencies have previously been measured by the focal plane vendor (Santa Barbara Research Center). However, spectral calibration at MIT/LL will determine the spectral response for each band as an assembled unit under vacuum and at flight operating temperature. These measurements will also determine the out of band response and spectral cross talk for each band.

Technique

The technique we have adopted for the EO-1 Advanced Land Imager consists of flooding the focal plane with a beam of narrow spectral width (2 nm FWHM) sequentially from 350 to 2600 nm in 2 nm intervals. At each interval, the beam is stabilized and the output of the focal plane is recorded. Spectrally calibrated silicon and lead sulfide detectors are also positioned within the beam to monitor the reference beam flux and stability.

Collimator

The spectral collimator is depicted in Figure 4. A 250W quartz tungsten halogen lamp is the source of broadband, featureless, stable emission from 350 nm to 2600 nm. An *Oriel MS257* double grating monochromator is configured to pass a 2 nm FWHM selection of input source spectrum with only $1x10^{-8}$ stray light. Once the beam exits the monochromator, it is spatially randomized by a 1.5" inner-diameter integrating sphere. A condensing lens is used to magnify the sphere exit port to approximate a 0.6° diameter object in the ALI field-of-view. The magnified image is placed at the focus of a 17-inch diameter off-axis parabola and the collimated beam is reflected off a 18-inch flat mirror, through a vacuum tank window and into the entrance aperture of the instrument. Reference silicon and lead sulfide detectors are mounted near the overfilled vacuum tank window to monitor beam flux and stability.

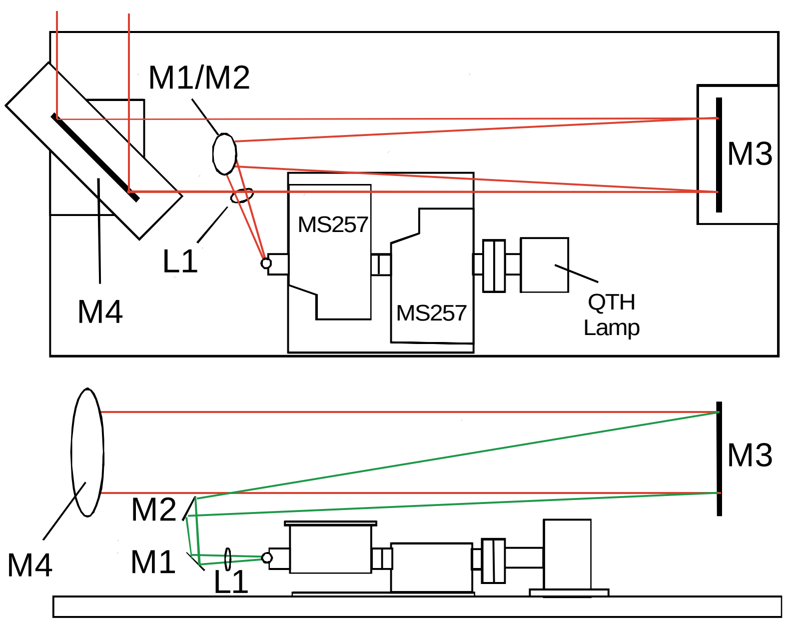

Figure 4: Collimator used for EO-1 spectral calibration.

Monochromator

The monochromator selected for spectral calibration is the *Oriel MS257* double monochromator. This system has an F4 entrance cone and each monochromator is supplied with a turret containing four gratings that cover the 0.3 – 2.6 μm spectral bandpass. Five long-pass filters are mounted on a filter wheel at the entrance of the double monochromator to block multiple orders of shorter wavelengths. Fully automated grating selection, wavelength specification, filter wheel position, and detector readout are controlled by *LabVIEW* code via GPIB commands from the ACCN.

5. RADIOMETRIC CALIBRATION

Radiometric testing of the EO-1 ALI determines the response of the focal plane to various intensities of incident radiation and is designed to calibrate the dynamic range and linearity of each pixel.

Technique

The technique we have adopted for radiometric calibration consists of flooding the entrance aperture with a diffuse source of stable, broadband emission at various radiance levels and recording the output of the focal plane at each level. The source of diffuse emission is a 30-inch diameter integrating sphere with a 10-inch diameter output port manufactured by *Labsphere Inc*. (Figure 5). This sphere contains three 150 Watt internally mounted and one 125 Watt externally mounted Halogen lamps and will provide a diffuse scene equivalent to 100% albedo from 600-2500 nm. This source will also provide a diffuse scene equivalent to 50% albedo from 400-600 nm. Additional radiance below 600 nm is provided by four 300 Watt externally mounted Xenon sources. Radiance levels will be generated by powering internal and external lamps incrementally. Additional levels will be provided by digital control of a linear attenuator positioned between the externally mounted halogen source and the sphere. Continuous broadband monitoring of the sphere stability is provided by silicon and germanium detectors mechanically mounted to the sphere wall.

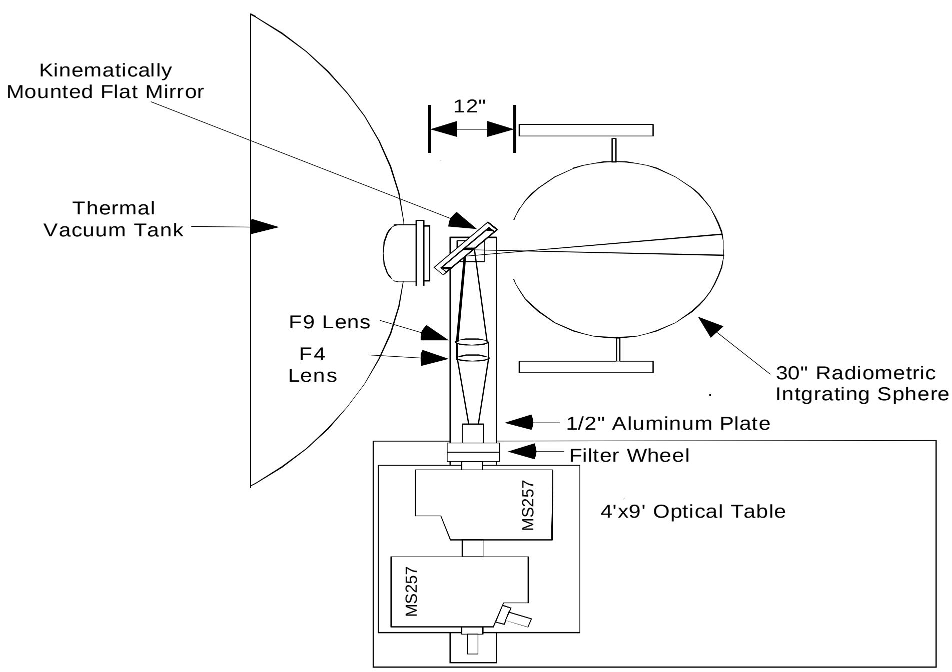

Figure 5: Radiometric calibration system for EO-1 ALI.

For each radiance level, the sphere will stabilize for 15 minutes. The response of the focal plane will then be recorded for several frame rates and integration periods. Finally, the ALI aperture cover will be closed and reference dark frames will be recorded.

Traceability to NIST

In order to provide absolute radiometric traceability to other sensors, a radiometric transfer standard monitoring system has been constructed (Figure 6). The principle components of the monitoring system are a NIST-traceable irradiance source and an *Oriel* double monochromator. The 250 Watt irradiance source is mounted on a post with proper baffling to control stray light from the room and reflections from the source off other surfaces. A standard radiance scene is generated by placing a *Labsphere Spectralon* (Leland and Arecchi, 1995) sheet 50 cm from the irradiance source. The monochromator field-of-view is limited to a 6.45 cm^2 region of the diffuse scene to maintain the traceability of the radiance source. A 6-inch flat mirror is placed between the *Spectralon* diffuser and entrance slit of the monochromator for convenient location of the source. The F9/F4 lenses are used to narrow the field-of-view entering the monochromator while maintaining the required F4 entrance cone. Alternately scanning the radiance scene produced by the standard lamp and various radiance levels output by the large integrating sphere, radiometric NIST traceability will be established for the EO-1 ALI.

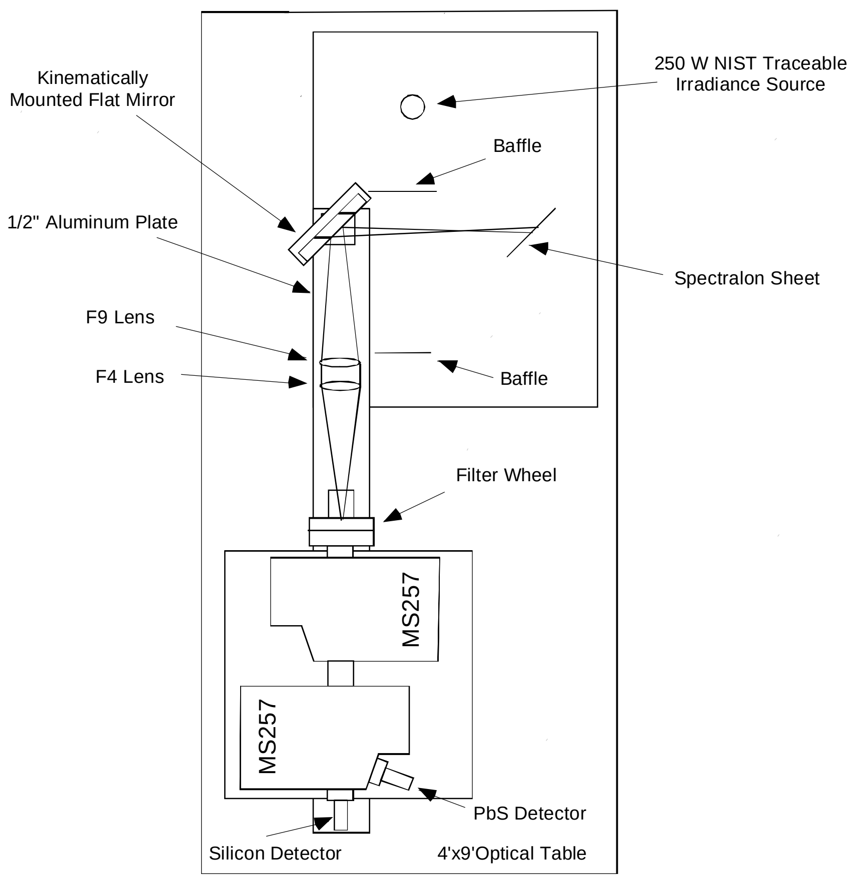

Figure 6: Laboratory configuration for NIST traceability to EO-1 ALI radiometric calibration.

In addition to establishing the general NIST traceability of the EO-1 ALI radiometric calibration, near real-time monitoring of the sphere radiance level will be accomplished by mounting a 6-inch flat mirror on a 12-inch post between the vacuum tank window and the integrating sphere. During radiometric calibration, the mirror is removed and the response of the focal plane is recorded. Between radiance levels, the mirror is kinematically mounted on the aluminum bar, redirecting a portion of the sphere radiance into the entrance slit of the spectroradiometer. The radiance of the integrating sphere is then measured from 300 to 2600 nm in 10 nm intervals with 5 nm FWHM resolution.

6. VERIFICATION OF IN-FLIGHT SOLAR CALIBRATOR

In addition to the spatial, spectral, and radiometric calibration of the ALI, measurements will be conducted during pre-flight calibration to verify a solar viewing technique to be used for in-flight radiometric calibration of the EO-1 ALI.

As a part of the in-flight radiometric calibration plan (Mendenhall et al., 1998), periodically, the instrument aperture cover will be closed, a *Labsphere* space-grade *Spectralon* diffuser will be placed in front of the ALI M2 mirror, and the instrument pointed in the direction of the Sun. After a brief stabilization period, a slide is withdrawn at a constant velocity, to expose a slotted mask (Figure 5), filling a portion of the aperture cover. This mask contains seven reference slots designed to provide a piecewise linear increase (decrease) of signal level from 0% to 90% equivalent diffuse Earth reflectance. As the slide is withdrawn, the solar flux entering through the exposed slot(s) will be diffusely scattered off the Lambertian *Spectralon* reflector, producing uniform scenes of incrementing radiance. Reference bars, located between the slots will provide a constant signal level for 0.5 seconds for each radiance level. Periodic absolute radiometric calibration of the focal plane will be maintained by recording the output of the focal plane as a function of calibration mask position (assuming constant solar irradiance from 400-2500 nm and stable *Spectralon* diffuser).

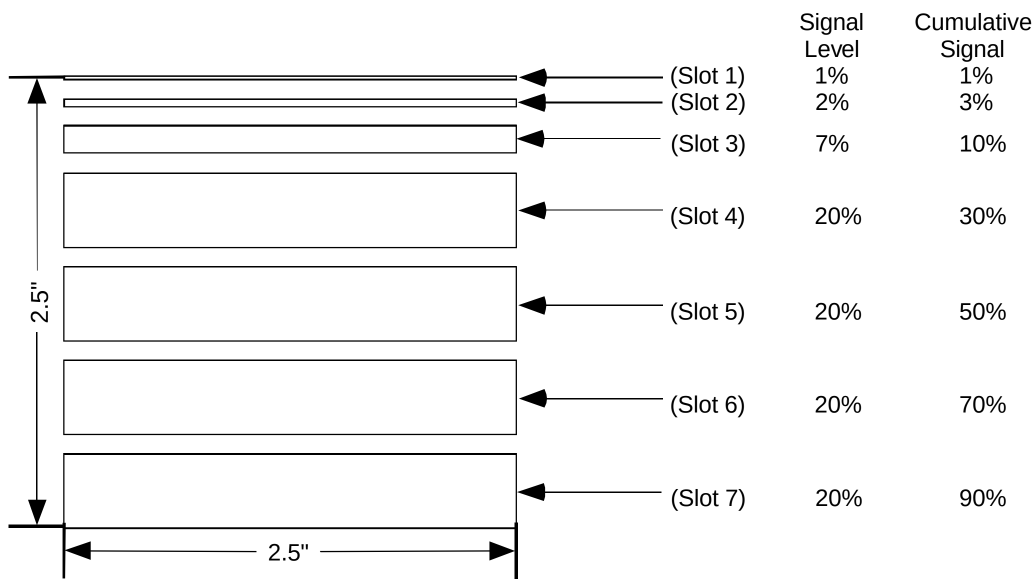

Figure 7: Aperture cover mask used during solar calibration

Figure 8 depicts the system to be used to validate the solar calibration technique at Lincoln Laboratory. The collimator is the same used for spectral calibration. The beam from an irradiance source is placed near the focus of a 17-inch diameter off-axis parabola and the collimated beam is reflected off a 18-inch flat mirror and into the entrance aperture of the instrument. An alternative source being investigated is the Sun itself. Taking advantage of a fortunate placement of the clean room, an image of the Sun, tracked using a heliostat, may be directed into the entrance aperture of the telescope using a series of external mirrors. In either case, a reference silicon detector is mounted near the overfilled entrance aperture to monitor beam flux and stability.

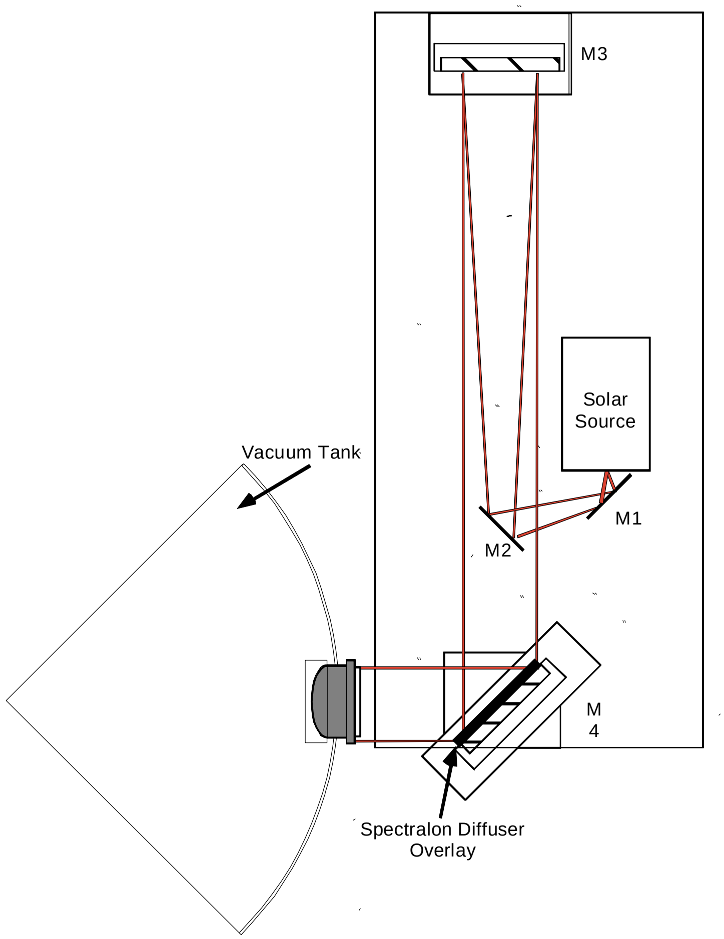

Figure 8: Collimator to be used for solar calibration verification. Initially, the *Spectralon* overlay is removed and data is collected using the ALI calibration slide and solar diffuser. Afterwards, diffuser plates doped to various albedo levels are placed in front of the collimator M4 mirror to provide reference scenes for standard ALI data collection. These data are then compared to verify the ability to radiometrically calibrate the ALI using the solar calibration technique.

The solar calibration validation technique itself centers on the accurate prediction of albedo levels based on accurately known reflectance standards. First, the aperture cover of the ALI is closed and the solar diffuser is placed in front of the M2 mirror. Next, the collimated source is turned on and allowed to stabilize. The aperture cover mask is then retracted at 0.5 cm/second and the focal plane response is recorded. Using these data, the radiometric calibration pipeline software is used to produce a set of pixel calibration coefficients relative to the laboratory source spectrum.

Once the above data are collected, direct measurement is made of the same irradiance source reflected off a diffuser of known BRDF placed in front of mirror M4. To accomplish this, a *Spectralon* sheet with measured BRDF will be placed at 45° immediately in front of mirror M4. The solar diffuser is then stowed, the aperture cover is opened, and the response of the focal plane viewing the *Spectralon* panel is recorded. This process is repeated with several panels doped to provide various albedo levels. The apparent BRDF of each *Spectralon* sheet may then be calculated by multiplying the calibration coefficients by the focal plane response to the illuminated panel. The result should be very close to independent laboratory BRDF measurements of the material. In this process, the spectrum and intensity of the laboratory source cancel out, so it is not required to be a true simulation of solar irradiance.

7. ACKNOWLEDGEMENTS

The authors wish to thank the following individuals of MIT Lincoln Laboratory: Mr. Berton Willard for his optical expertise in designing the imaging collimator and Mr. Eric Ringdahl, Mr. Patrick Quinn, and Mr. Frank Perry for their technical assistance in designing and testing equipment in the laboratory.

8. REFERENCES

Digenis, C. J., Lencioni, D. E., and Bicknell, W. E., Proc. SPIE, This volume, 1998.

Lauer, D. T., Morain, S. A., and Salamonson, V. V., Photogramm. Eng. and Remote Sens., 6, 831, 1997.

Leland, J. E., Arecchi, A. V., Proc. SPIE, 2475, p. 384, 1995.

Lencioni, D. E., and Hearn, D. R., "New Mellennium EO-1 Advanced Land Imager", *International Symposium on Spectral Sensing Research*, San Diego, Dec. 13-19, 1997, Int. Soc. For Photogrammetry & Remote Sensing, 1998.

Mendenhall, J. A., Lencioni, D. E, Hearn, D. R., and Parker, A. C., Proc. SPIE, This volume, 1998.

Schowengerdt, R. A., Archwamety, C., and Wrigley, R. C., Photogramm. Eng. Remote Sens., 51, 1395, 1985.